MEASUREMENT AND PREDICTION OF THERMAL EXPANSION COEFFICIENT OF CFRP COMPOSITES AT LOW TEMPERATURE

Wonoh Lee, **Sang-Bok Lee and Moon-Kwang Um**

Composite Materials Research Group, Korea Institute of Materials Science,
797 Changwondae-ro, Changwon, Gyungnam 641-010, South Korea

Introduction

Due to the structural stability and performance, fiber reinforced polymeric (FRP) composites have been paid attention as the candidate materials for low temperature storage tanks in the aerospace and LNG transport applications [1]. Therefore thermal properties of composite materials should be well characterized at the low temperature environment and precise numerical techniques are required for the structural design.

Conventional measurement method for CTE is to use dilatometer, interferometry or laser instrument [2,3]. Here, CTE was measured by utilizing the strain gage, which can guarantee the accuracy at the low temperature [4]. For the prediction of CTE, there have been several methods such as a simple rule of mixture, a homogenization of cell modeling [5] and finite element (FE) analysis using representative volume element [6]. However, the accuracy was insufficient since many methods use temperature-independent properties based on material supplier's data.

In this work, two simple and accurate prediction methods (analytic and FE based calculation) were suggested for CTE of the carbon fiber reinforced polymer (CFRP) composite system considering temperature-dependent material behaviors and CTEs of fiber and polymer matrix. Through the inverse FE calculation for the unit cell of the composite, the CTE of the carbon fiber is determined to follow the thermal behavior of the CFRP composite. Considering different matrix based CFRP composites, the prediction capability was examined by utilizing the inversely determined CTE of the carbon fiber.

Experiment

Materials

The carbon fabric was a plain weave (TR-30S) and epoxy resin was considered for the CFRP composite. To investigate the effect of different matrix system, CTBN rubber modified epoxy resin was also considered.

Measurement of CTE using Strain Gage and Elastic Modulus at Low Temperature

In this work, two quarter-bridge type strain gage circuits are considered for the measuring sample and the reference specimen (titanium silicate). The thermal output (ε_{TO}) is a function of CTEs of both sample (α_S) and strain gage (α_G) as well as a thermal coefficient of resistivity of strain gage (β_G) as described in Eq. (1).

$$\varepsilon_{TO} = \left[\beta_G / F_G + \left(\alpha_S - \alpha_G\right)\right]\Delta T \tag{1}$$

where F_G is a gauge factor and ΔT is temperature change. Considering the thermal output difference between the sample and the reference specimen (R), CTE of the sample becomes

$$\alpha_S = \alpha_R + \left(\varepsilon_{TO(S)} - \varepsilon_{TO(R)}\right) / \Delta T \tag{2}$$

since α_R is known [7]. Here, thermal outputs were measured from room temperature (RT) to -100°C considering thermal equilibrium. Also, elastic modulus was measured at RT, 0, -30, -60, -100°C to determine the thermal dependency.

Prediction Models

Analytic Method

Based on the classical rule of mixture, the thermal strain of composite becomes

$$\varepsilon_C^T = \left(c_f E_f v_f \varepsilon_f^T + E_m v_m \varepsilon_m^T\right) / E_C \tag{3}$$

where subscripts *f*, *m* and *C* represent fiber, matrix and composite. Considering temperature dependency in Eq. (3), CTE of composite becomes

$$\alpha_C = \frac{1}{E_C^2}\left[E_C Q(T) - \frac{dE_C}{dT} P(T)\right] \tag{4}$$

where

$$P(T) = c_f E_f v_f \int \alpha_f dT + E_m v_m \int \alpha_m dT \tag{5}$$

and

$$\begin{aligned} Q(T) = {} & c_f v_f \left(\frac{dE_f}{dT} \int \alpha_f dT + E_f \alpha_f\right) \\ & + v_m \left(\frac{dE_m}{dT} \int \alpha_m dT + E_m \alpha_m\right) \end{aligned} \tag{6}$$

Inverse FE analysis based Model

Considering the unit cell as shown in Fig. 1, numerical FE simulation was performed for the thermal compaction. In order to find the CTE of carbon fiber, inverse calculation was carried out to fit minimize the

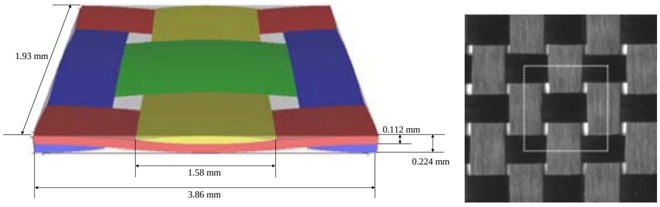

Fig. 1 Unit cell structure for FE calculation

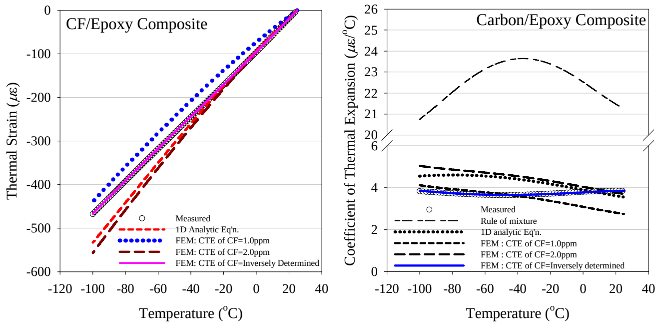

Fig. 2 Thermal strain and CTE of carbon fiber/epoxy composite

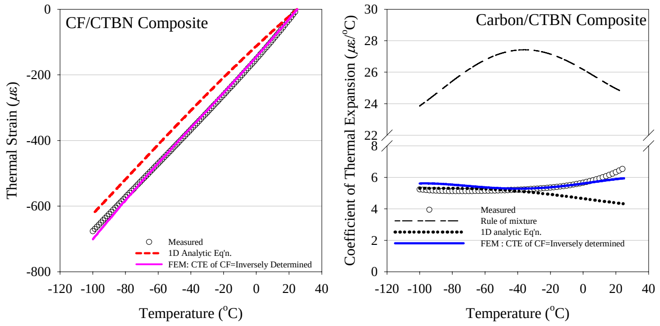

Fig. 3 Thermal strain and CTE of carbon fiber/CTBN modified epoxy composite

difference between experimental results and calculation data using the Newton-Raphson method. Here the commercial FE software, ABAQUS/Standard was utilized.

Results and Discussion

Fig. 2 shows the CTE and thermal strain of carbon fiber calculated from the inverse FE analysis for the carbon fiber/epoxy composite. As shown in figures, the inverse method correctly follows the experimental data. Also the result by the analytic model and constant CTE based FE analysis gave good agreement with experimental result. However, the tendency is slightly different. As expected, the simple rule of mixture showed large deviation due to ignoring of temperature-dependent behaviors.

In order to verify the developed CTE prediction methods, the same FE simulations were performed for the carbon fiber/CTBN-epoxy composite. The numerical results were compared with experimental results as shown in Fig. 3. In this case, the inverse FE analysis showed better agreement than the analytic model. Even though the order of values are almost similar each other, the tendencies were opposite. Since the crimping geometry is ignored in the analytic model, such discrepancy occurs at the different composite system.

Conclusion

In this work, an analytic model and FE analysis based method were suggested to predict CTE of carbon fiber composite at low temperature. Through the inverse numerical calculation, CTE of carbon fiber was estimated to exactly follow the thermal contraction behavior of plain weave composites. Utilizing this, the thermal behavior was calculated for the different matrix system such as a carbon fiber/CTBN epoxy composite and results showed that the FE analysis method gave better agreement than the analytical model with experimental results. However, the orders of CTE value were almost same from both methods. Therefore the simple analytic model can be applied for adequate temperature range. Once temperature variation is severe, the inverse FE analysis based method is recommended for the accuracy.

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